U. S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE

OFFICE NOTE 144

Plans of the National Meteorological Center for Numerical Weather Prediction

Frederick G. Shuman
National Meteorological Center

APRIL 1977

I. Currently operational NMC models.

The U. S. National Meteorological Center (NMC) has a variety of atmospheric models both in operation and under development. In operation now are five distinct models, each with its own specific purposes.

Table I is to assist you in understanding Section I.

Table I. NMC operational models, January 1, 1977.

Starting time after 00 & 12 GMT	Model	Area	No. of Levels	Grid size	Forecast period
01:15	Barotropic-mesh	Hemisphere	2	381 km at 60N	48 hr
01:30	LFM	North America	6	190.5 km at 60N	48 hr
04:00	6L PE	Hemisphere	6	381 km at 60N	00 GMT: 84 hr 12 GMT: 48 hr
07:30	MFM	$3000 \times 3000\ km^2$	10	60 km	48 hr
10:00	9L GLOBAL	Global	9	2.5° latitude	00 GMT: 6 hr 06 GMT: 6 hr 12 GMT: 6 hr 18 GMT: 18 hr

1. The barotropic-mesh model is basically a barotropic model that employs the filtered equations for the 500 mb level. It is meshed with an 850-500 mb thickness vorticity equation to provide a second prediction level at 850 mb, which is used internally to estimate surface drag and topographical effects. No other physical effects are included. It covers the northern hemisphere, with a square mesh of points separated by 381 km on a polar stereographic projection true at 60N.

The Barotropic-mesh Model has a triple purpose. It is started at H + 01:15, H being one of the synoptic hours, 00:00 GMTor 12:00 GMT. As a model that runs very quickly on the computer, it provides the field forecaster with an early prediction from the latest data. As a relatively simple and easily understood model, it gives the forecaster considerable insight as to why the atmosphere evolves as it does. In addition to climatology and persistence, it provides an excellent base of skill for the verification of more sophisticated models.

2. The Limited-area Fine-mesh Model (LFM) has in the past few years become the model that fulfills most of the everyday requirements for domestic guidance. It is started at H + 01:40, and is run to 48 hr. The LFM covers North America and nearby waters, with grid points separated by 190.5 km at 60N. It employs the primitive equations in six layers, centered at about 133, 200, 344, 567, 789, and 950 mb. Physical effects include surface drag, topographical effects, feedback of latent heat, convective parameterization, and long and short wave radiation. It provides guidance for quantitative precipitation forecasting (QPF) in the form of charts of 12 hr accumulations of precipitation.

All of the NMC models, except the Barotropic-mesh, include the same physical effects, although they vary in their sophistication. Similarly, they all provide QPF guidance.

3. The Six Layer Primitive Equation model (6L PE) satisfies requirements for guidance over areas of the northern hemisphere not covered by the LFM. The principal such requirements are for commercial aviation and maritime interests. It is also used in the NMC five-day forecast program, provides lateral boundary conditions for the LFM, and satisfies the international commitments of NMC to the World Weather Watch (WWW). The 6L PE is cast in the same basic framework as the LFM, but it covers the northern hemisphere, and its grid size is double, 381 km at 60N. It is run at H + 04:00, to 48 hr from 12:00 GMT data, and to 84 hr from 00:00 GMT. Following the 84 hr run, the prediction is extended to 168 hr with the Barotropic-mesh model.

4. The Moveable Fine-mesh Model (MFM) was originally designed to predict paths of hurricanes. It is the most highly resolved model run operationally at NMC, with 10 layers and a 60 km mesh. It covers an area about the size of the 48 contiguous United States. It is on call, and not run regularly. It is called when an Atlantic hurricane threatens the North American continent, and also by hydrologists of the National Weather Service when there is a threat of flash floods in the United States.

The area of the MFM is relocateable, to cover the "problem of the day." When the problem is a hurricane, it is run in such a mode that the center of its area is kept in coincidence with the hurricane's center. Thus, the word "moveable," is in its name. When called, it is run to 48 hr at H + 07:30. Since June 1, 1976, it has been called about 40 times.

5. The Nine Layer Global model (9L GLOBAL) is the only global model that is now run operationally, and principally serves to provide a first guess for analyses. Its framework is similar to the 6L PE, but it has some important departures. Instead of a square mesh on a polar stereographic projection, grid points are separated by a uniform interval of latitude and longitude, namely 2.5°. Additional numerical devices are required to satisfy the Courant-Friedrichs-Lewy stability criterion (CFL), because of the small separation of grid points in high latitudes. The 9L GLOBAL is run at 10:00 GMT for two 6 hr periods from 00:00 and 06:00 GMT data; and at 22:00 GMT for a 6 hr period from 12:00 GMT data, and for an 18 hr period from 18:00 GMT data. The 18 hr forecast provides back-up in case of hardware or software failure during the two subsequent 6-hr cycles run at 10:00 GMT.

II. NMC plans for 1977

NOAA replaced a complex of three CDC-6600's with a complex of two IBM 360/195's in March 1974, and added a third in November 1975. The high speed of the IBM machinery, 10-15 million instructions per second (MIPS), compared to that of the CDC-6600, 2 MIPS, is required for advances in modelling, particularly for models with higher resolution. To date, NMC has enlarged the area covered by the 6L PE from 53 x 57 grid points to 65 x 65, and has extended the forecast period of the LFM from 24 to 48 hrs, but has otherwise not used the full power of the new system in operations. A number of experiments with more highly resolved models have been carried out, however, and NMC has recently formulated definite plans for replacing both the LFM and the 6L PE this year.

Table II shows the NMC operations projected for the end of 1977. It should be of assistance in understanding section II.

In the case of the LFM, the plan is to replace it with essentially the same model, but with the grid size roughly halved. The exact new grid size will be adjusted so that no more than 30 min per 48 hr forecast will be added to its running time. There will be no change in area covered. In order to achieve nearly half grid size with these limitations, a technique that was used operationally on the CDC 6600 will be introduced. By time-averaging the pressure-force terms in the equations of motion, the time step for a given horizontal resolution can be doubled without violating the CFL stability criterion. It will also be necessary to optimize the machine program.

In case of the 6L PE, NMC is considering three candidates for its replacement.

1. Essentially the same model, covering the same area, but with half the grid size. Like the new LFM, it will incorporate the technique of pressure-force-averaging, and its machine code will be optimized.

2. The 9L HEM, which is a version of the 9L GLOBAL, but with intervals between points reduced to 2°, and over an area reduced to hemispheric.

Table II. NMC operational models, 1978.

Starting time after 00 & 12 GMT	Model	Area	No. of Levels	Grid size	Forecast period
01:15	Barotropic-mesh	Hemisphere	2	381 km at 60N	48 hr
01:30	LFM-II	North America	6	127 km at 60N	48 hr
04:00	One of:				00 GMT: 84 hr 12 GMT: 48 hr
	a. 6L PE-II	Hemisphere	6	190.5 km at 60N	
	b. 9L HEM	Hemisphere	9	2° latitude	
	c. NGM: Grid A	Hemisphere	8-10	448 km	
	Grid B	25000 x 25000 km^2	8-10	224 km at 60N	
07:30	MFM	3000 x 3000 km^2	10	60 km	48 hr
10:00	9L GLOBAL	Global	9	2.5° latitude	6 hr cycle and "catch-up" (See text)

3. A Nested Grid Model, referred to as NGM. This model differs in many ways from NMC operational models. Its numerics are quite different, being phrased in forms that are conservative in Arakawa's sense. Perhaps the most fundamental difference, however, is the use of nesting itself. It has a coarse grid (448 km at 60N) covering the hemisphere, and a double resolution grid (224 km at 60N) covering a smaller area. Referring to these two grids as A and B, it has the capability for a third grid, C, with quadruple resolution (112 km at 60N) within grid B covering an even smaller area. The third grid, C, is not being considered for early implementation, however, due to its additional running time. One of the features of this model is that grid B (and grid C as well) is relocateable. In operation, the location of grid B would be chosen to cover the "problem of the day." The nesting, in a sense, performs the functions of both the LFM and 6L PE, but the various grids are fully interactive, that is, calculations on the finer grids feed-back into coarser grid calculations, as well as vice versa. The vertical dimension will be resolved with 8-10 levels.

The hard limitations placed on the design of these three models are that they must not add more than 48 min running time per 48 hr forecast, and they must cover the hemisphere.

The target for implementing the new LFM is June 1, 1977.

The process of implementing the 6L PE replacement is more complicated. The three candidates will be tested and evaluated on seven special cases, and one will be selected for a full-blown comparison with the operational 6L PE. The target for this selection is June 1, 1977. The candidate selected will then be compared with the operational 6L PE on about 30 special cases, to determine that it indeed does have increased skill. The target for implementation is September 1, 1977.

Besides the plans to replace the LFM and the 6L PE, NMC is planning another change in 1977. It involves the global analysis system, and therefore will not be so visible to outside users. The present global analysis system consists of fitting Hough functions to observed data. Hough functions are solutions to Laplace's tidal equation, which imply a near-geostrophic relation between the wind and mass fields. The wind and mass fields are therefore analyzed simultaneously. In view of the mix of wind, temperature, and pressure observations of World Weather Watch, this is an advantage. One disadvantage, however, is that the varying accuracy of the various kinds of observations is not properly taken into account. NMC now believes the latter outweighs the former, and is developing an optimum interpolation system that will account for the statistics of the errors in rawinsonde observations, winds found by tracking clouds from satellites, indirect soundings from satellites, etc. In preparation for FGGE, the target for implementing the new analysis system is October 1, 1977.

The currently operational six-hourly analysis cycle provides a ten-hour hold on 00:00 GMT and 12:00 GMT data, but only a four-hour hold on 06:00 GMT and 18:00 GMT data. In November 1977, in preparation for FGGE, NMC plans to increase the holding time on all data. At 10:00 GMT six-hour predictions will be made with 9L GLOBAL from 18:00 GMT and 00:00 GMT analyses, and at 22:00 GMT from 06:00 GMT and 12:00 GMT analyses. Thus the hold on 00:00 GMT and 12:00 GMT data will remain 10 hr, but will be increased from 4 to 16 hr on 06:00 GMT and 18:00 GMT data. With the analysis cycle running so far behind the atmosphere, two additional "catch-up" analyses and 6 hour runs will have to be made to provide first guesses and analyses for the forecast model runs.

III. What should be expected from the new 1977 NMC models?

NMC has mounting evidence that the key now to advances in operational numerical weather prediction is reduction of truncation error. Truncation error is a purely mathematical error, and occurs when finite-difference ratios replace derivatives in the basic meteorological equations. Given digital rather than analog computers, there are at least three ways to reduce truncation error.

The most straightforward way is to reduce the distance between grid points. This is the path NMC has chosen for the immediate future, but it is a road with a high toll. The vertical resolution seems not to be so critical, nor does time resolution, but the CFL stability criterion requires that the time step must maintain a fixed ratio to the horizontal grid interval. Thus if r is the reduction factor applied to the grid interval, the number of points in space and time at which calculations must be made increases by a factor of $(1/r)^3$. For example if the grid interval is halved, then $r = \frac{1}{2}$, and the calculations increase by $2^3 = 8$. The combination of operational deadlines and computer speed therefore places a quite distinct limitation on grid size.

Another way to reduce truncation error is to make more accurate estimates of the derivatives. This can be done by including in the estimates more points than the two closest neighboring ones. In principle this can be done with minimal cost, but considerable research and development remains to be done. NMC is pursuing this approach.

Yet another way is to phrase the equations in terms of amplitudes of orthogonal functions, such as spherical harmonics. No truncation error is made on the functions that are included, but virtually an infinite number of such functions are required to completely describe the state of the atmosphere. This approach then has its own kind of "truncation error," different from finite differences, and arising from those functions not included. The cost of including more functions is similar to the cost of increasing the resolution of finite-difference models. This approach is very attractive, however, is operational in Australia and Canada, and NMC is well along on the development of a "spectral" model.

Two sets of statistics will be offered here, to indicate the effect of resolution on skill. Then results will be discussed, taken from runs with five models, all with different resolutions.

Figure 1 shows skill of the LFM and 6L PE averaged over the twelve months, December 1975 through November 1976. The measure of skill is based on Teweles and Wobus' S1 score. Although the score has a mathematical range of 200, it has been determined at NMC that at 500 mb, a chart with a score of 20 is virtually perfect, and one with a score of 70 is worthless. At sea level the corresponding numbers are 30 and 80. "Skill," as shown in Figure 1, then, is related to S1 as follows:

$$\begin{aligned} \text{500 mb} &: \ \% \text{ skill} = 2(70 - \text{S1}) \\ \text{sea-level} &: \ \% \text{ skill} = 2(80 - \text{S1}) \end{aligned}$$

Figure 2 shows threat scores for 12 hr measurable precipitation at 60 U.S. stations averaged for April, May, and June 1975. The threat score is

$$TS = \frac{100H}{F+O-H}$$

where H is "hits," the number of correct forecasts of precipitation, F is the number of forecasts of precipitation, and O is the number of occurrences of precipitation. "C" in Figure 2 denotes the coarse mesh 6L PE, and "F" the fine mesh LFM. It should be noted that not only is the LFM more skillful than the 6L PE in each period, but its improvement can be translated into a 12 hour advantage.

These kinds of statistical comparison were the earliest objective information developed at NMC about the effect of resolution on forecast quality. In visual examination of the daily forecast charts, however, it was seen that on "run-of-the-mill" cases, the LFM makes only marginal improvements. Its outstanding improvements are made on infrequent cases of storm development and smaller scales generally. Being infrequent, such benefits tend to be lost in overall statistics. Precipitation is usually on smaller scales than other atmospheric parameters, and consistent with the smaller truncation error of the LFM, it shows a greater improvement in predicting precipitation quantitatively than in the case of other parameters. Quantitative precipitation, however, is still the most poorly forecast of all predicted variables. It is thought at NMC that this problem will yield to even higher resolution than the LFM. More than any other, this is the reason behind the new LFM with a smaller grid.

Figures 3 and 4 show graphically the effects of varying resolution for a selected case. Based on several cases, the sequence shown is typical of what should be expected regarding resolution vs. skill. The case is of an incipient frontal wave initially over the Gulf of Mexico, that developed in 48 hr and moved to the conjunction of Indiana, Ohio, and Kentucky. Figure 3 shows the 48 hr sea-level forecasts, proceeding left to right and top to bottom, made with the 6L PE, the LFM, the MFM with a 120 km grid, a version of the LFM with its grid reduced to 95 km (at 60N) and its area reduced to 1/4, and the MFM with its 60 km grid. The observed verifying chart is shown in the lower right panel.

Note that the 6L PE did not capture the important events at all, but progressive skill is shown by the other models as the grid size is reduced, especially in the location of the low center. It should be noted that the difficulty of the MFM (60 km) over the Gulf tier of states is probably due to boundary problems. Its southern boundary is just about at the border of the display. In this run, its boundary values were taken from the 6L PE, and so it could not properly close off the low to the south. Note that it did, however, exactly place the low center.

Of significance to forecasting the weather itself, Figure 4 shows the corresponding predictions of 12 hr accumulations of precipitation. Again, progressive skill is shown as resolution is increased.

IV. Things to do before 1980.

As the resolution of operational models is increased, they should respond more clearly to physical effects. The major effort will therefore be devoted to improvement of model physics.

The NGM, with all three grids (448, 224, and 112 km at 60N) will be tested for possible implementation as a single substitute for both the hemispheric model and the LFM-II. Although the NGM has the virtue of simplifying output for field use, the fact that calculations are done simultaneously on all grids will raise basic questions about operational schedules.

The global spectral model under development will be a candidate for replacing both the hemispheric model, perhaps in a global version, at H + 04:00, and the 9L GLOBAL at H + 10:00. It will first be tested as a possible replacement of the 9L GLOBAL, probably during 1978.

Considerable effort will also be devoted to analysis methods. The method of optimum interpolation presently being developed contains many compromises for operational use. Many of the error specifications, such as error covariances of satellite observations, must be improved. Variational analysis will also be studied as a supplement to optimum interpolation. Moisture analyses must also be improved.

V. NMC plans for the 1980's decade.

Several computers more powerful than the IBM 360/195 are already on the market. Early in the 1980's computers more than 10 times as fast as the IBM 360/195 are expected both to be available and to have been proven reliable. The evidence now available does not indicate that even the most highly resolved models have yet approached optimum resolution, particularly for quantitative precipitation forecasting. The present estimate, then, is that acquisition of new machinery will be required. Because of the inevitable delays in the budgetary process, January 1978 has been set as a target for justification of such an acquisition. The problem simply stated is one of showing that model resolution beyond the capabilities of the present machinery will result in an increase in accuracy that will justify the cost of a more powerful machine.

If it is assumed that even the new computers will not be capable of running a model with optimum resolution over an area larger than an octant of the globe, models will be run with a higher resolution over North America and nearby waters than elsewhere. For this reason, as well as the overriding importance to the United States of forecasts over North America, NMC plans to concentrate on that area. In preparing for the 1980's, the plan of NMC is to compare forecasts of models with various resolutions, with special emphasis on quantitative precipitation forecasts. The inventory of models at NMC includes enough basically different models to do the job, and not run the danger of drawing false conclusions due to model-dependent, as against resolution-dependent, errors. Three basic models will be used. In the following, resolution will be indicated by the grid size at 60N in parentheses.

1. The 6L PE (381 km), 6L PE (191 km), LFM (191 km), and LFM (95 km).

2. The NGM (448, 224, 112 km), and NGM (224, 112, 56 km).

3. The MFM (120 km) and MFM (60 km).

Where possible, models will be run with the same high-resolution analysis, in order to avoid the question of analysis-dependent errors. Testing is planned to begin in July 1977 on selected cases.

VI. Medium range weather forecasts.

NMC is now formulating plans to begin a ten-day forecast operation. Planning has not proceeded far enough to give details of such an operation, but it may begin before 1978.

During the past year NMC has been conducting experiments with an atmospheric model running to 10 days and longer. The model used is similar to the 9L GLOBAL, but with much lower resolution in both the horizontal and vertical. It has three layers, and grid points are separated in the horizontal by 3.75° of latitude and longitude. It covers the globe, and will be referred to here as the 3L GLOBAL. It has been used extensively for several years as a test bed for numerical systems. With its low resolution, it only takes about two hours running time for a ten-day forecast.

Although a program has not yet been developed to objectively verify the automatic 10-day forecasts, they have shown considerable skill on the scales contained in five-day mean charts. During the winter of 1976-77, the model was run to ten days on 15 week-ends. Five-day mean circulation charts at 500 mb, centered at day 3 and day 8, were produced, and manually interpreted in terms of five-day mean surface temperatures and precipitation. For the interpretation the analyst had available objective statistical tools that have been used for many years in the five-day forecast program. The temperature was predicted in five categories. With the climatological probability in parentheses, the categories were: much above (1/8), above (1/4), near normal (1/4), below (1/4), and much below (1/8). Similarly, except in arid areas precipitation was forecast in the three categories: above (1/3), near normal (1/3), and below (1/3). In arid areas only occurrence and non-occurrence was predicted. The same parameters are predicted in the same categories in the five-day program.

Figure 5 shows several Heidke skill scores that should shed some light on the skill to be expected of the 10-day forecasts. Several scores from the five-day program are also shown for comparison. Before 1970, days 2-6 were predicted thrice weekly, but since then five-day forecasts for days 1-5 have been made daily. The first two scores, 18.9 for the old program, and 46.7 for the new, indicate that the new program, based more heavily on machine guidance, is far more skillful than the old. This in itself should raise the question of whether 5 days is the limit of useful predictability. Indeed, the score of 18.2 for the subjective 6-10 day forecasts compares very favorably with the skill of 18.9 achievable for days 2-6 before 1970. Note that in last winter's five-day program, the man roughly doubled the skill of the machine guidance. Although scores for the 6-10 day machine guidance are not available, there is every reason to believe that the man's contribution to skill was great.

The weather during the winter of 1976-77 was unusually persistent, which might raise the question of the representativeness of skill during that period. The two scores using persistence for 6-10 day forecasts show that persistence was not the only factor in the relatively high score of 18.2.

The three scores for precipitation forecasts show similar advances in the five-day program, and indicate that 6-10 day forecasts are now feasible.

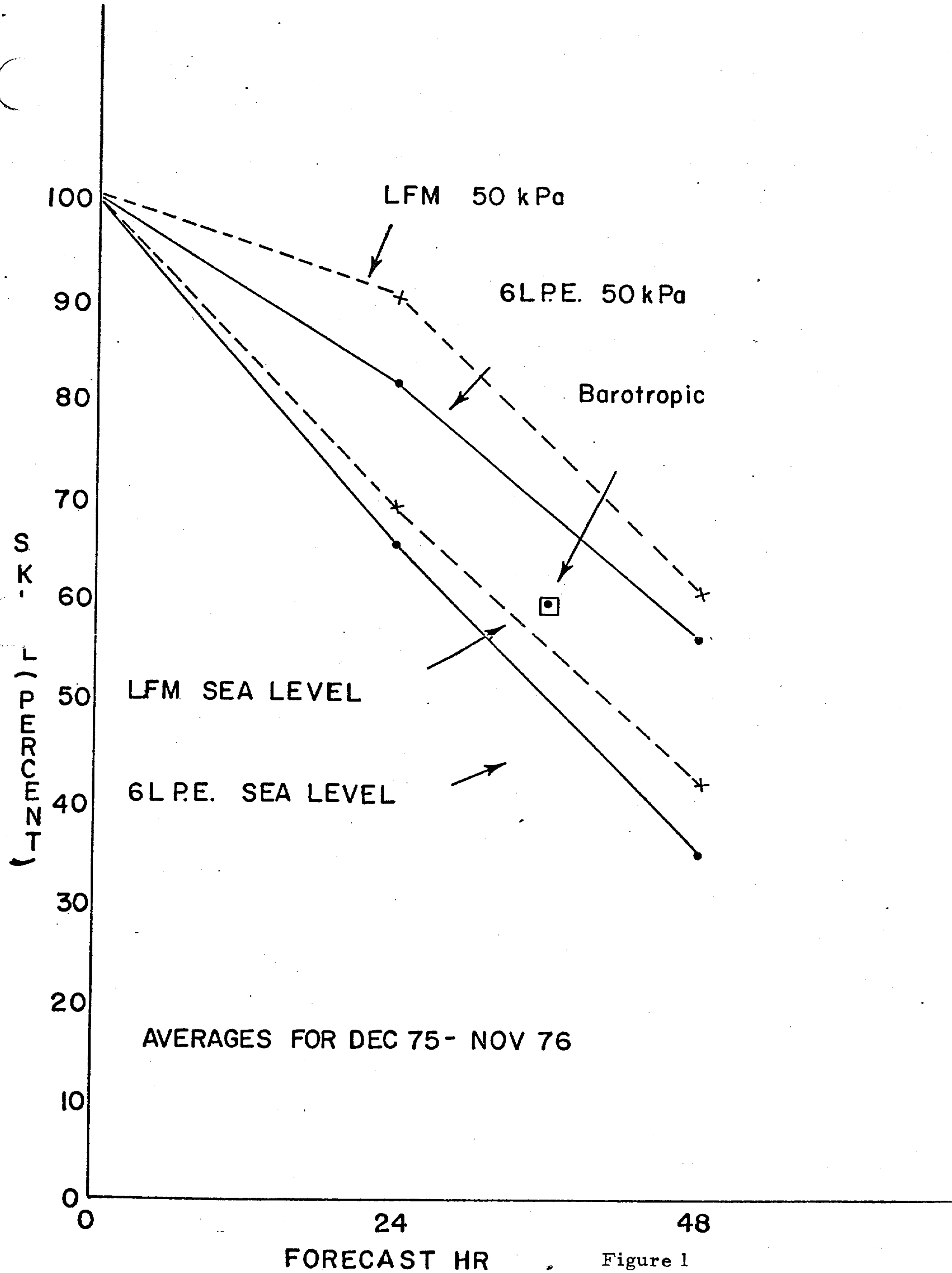
LFM 50 kPa
6L P.E. 50 kPa
Barotropic
LFM SEA LEVEL
6L P.E. SEA LEVEL
AVERAGES FOR DEC 75 - NOV 76
SKILL (PERCENT)
100
90
80
70
60
50
40
30
20
10
0
0
24
48
FORECAST HR

Figure 1

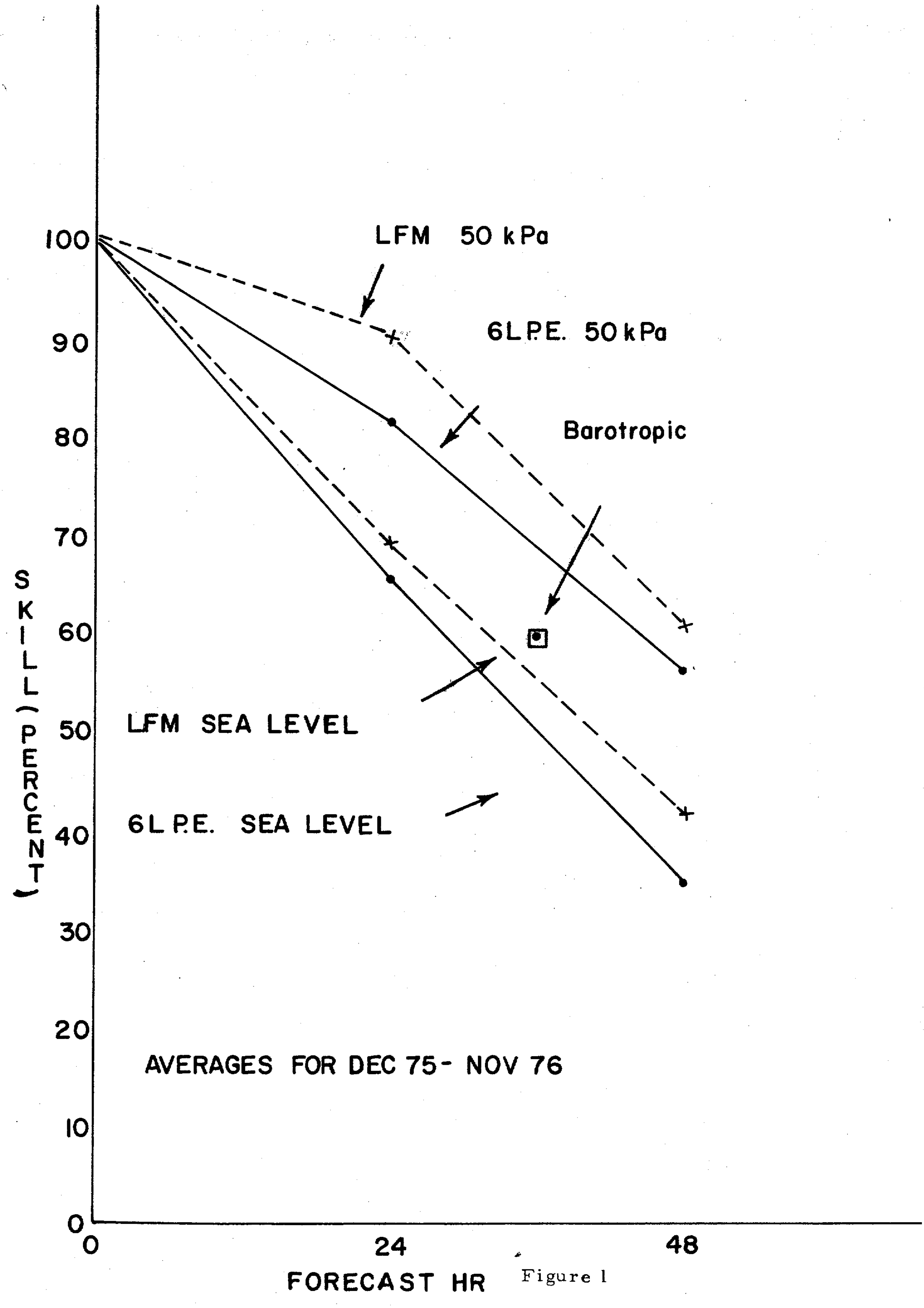
LFM 50 kPa
6LPE. 50 kPa
Barotropic
LFM SEA LEVEL
6LPE. SEA LEVEL
AVERAGES FOR DEC 75 - NOV 76
SKILL (PERCENT)
100
90
80
70
60
50
40
30
20
10
0
0
24
48
FORECAST HR

Figure 1

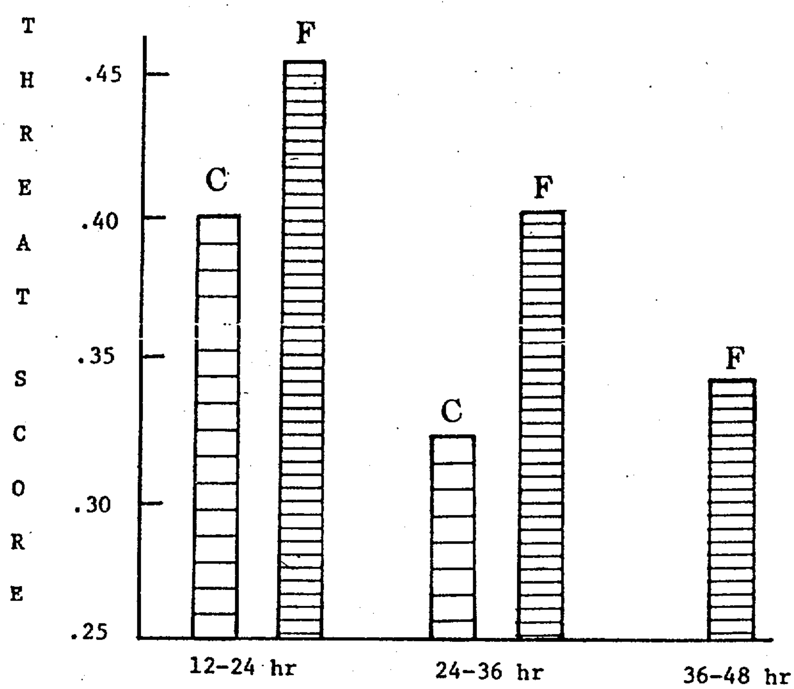

Figure 2

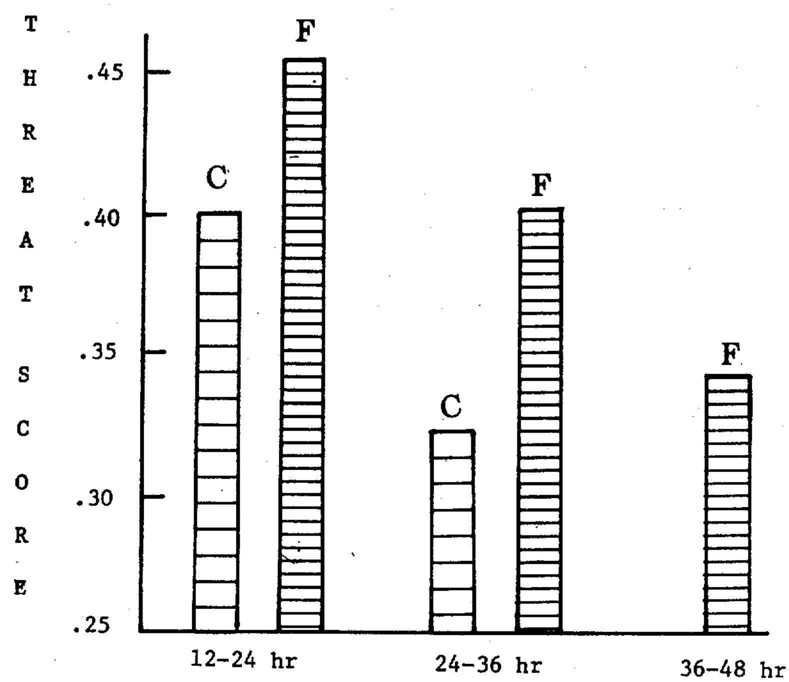

Figure 2

48-SURFACE FORECASTS

VALID TIME 1200GMT 26 DECEMBER 1975

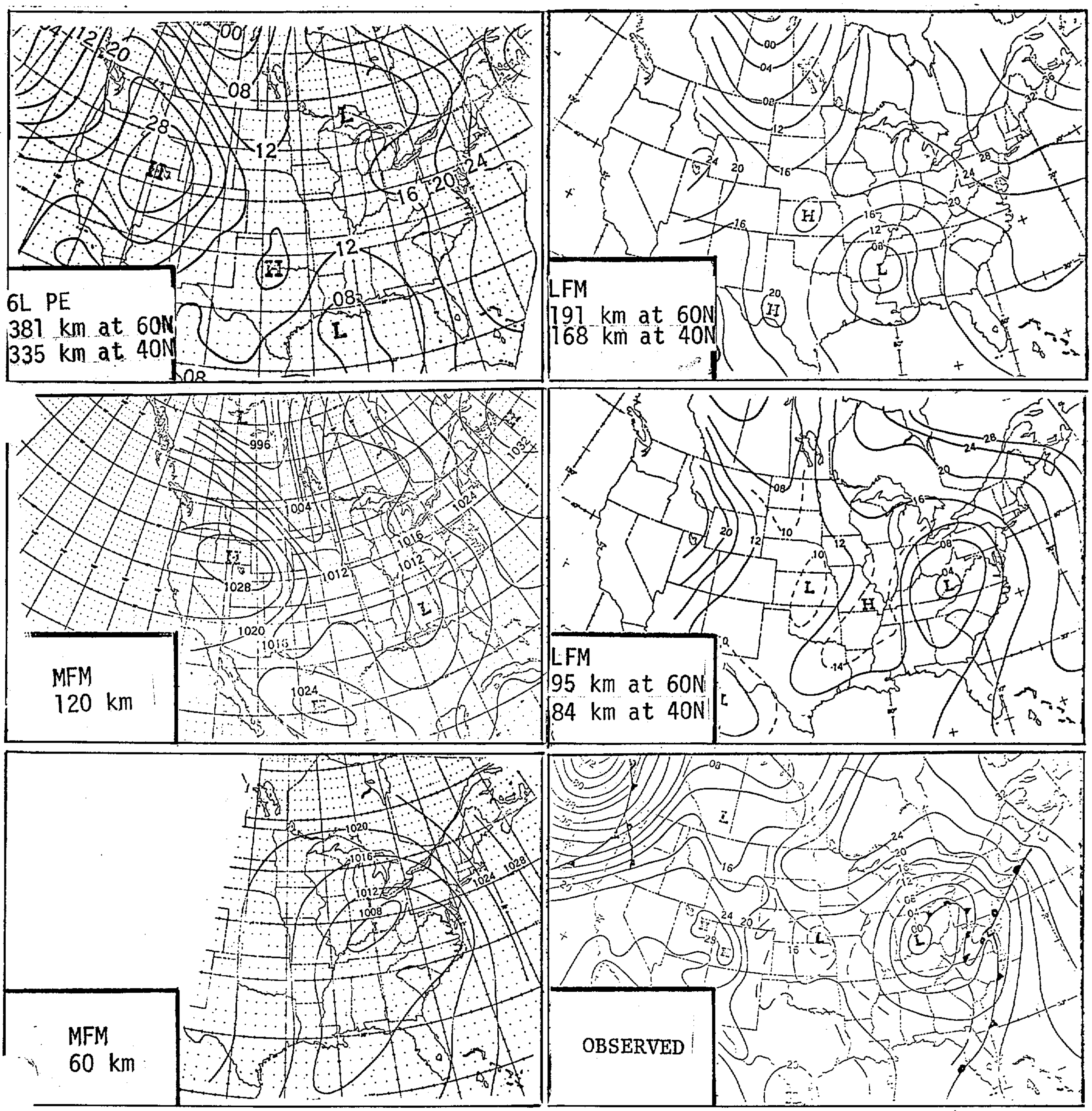

Figure 3